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NSDD Partnership

Working Together to Prevent Nuclear Trafficking

The Office of Nuclear Smuggling Detection and Deterrence

Poland Peer-Peer Engagement: Primary and Secondary Inspection

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Overview

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I. **Contamination Detection vs. Smuggling**
II. **Low Sigma Alarms and Their Importance**
III. **Gamma-Only Alarms and Special Nuclear Material**
IV. **Profile Analysis Pitfalls**
V. **Energy Windowing**
VI. **Neutron Alarms-Various Possibilities**
VII. **Alarm Adjudication (other presentation)**

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I. Contamination Detection vs. Smuggling

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- **Contamination: the unintended presence of radioactive materials in or on the surface of materials**
  - **Usually spatially dispersed on surfaces or entrained in bulk materials**
  - **Contaminated steel products-lost source in scrap: Mexico**
  - **Contaminated car shipments from Japan: Fukushima** ← **NSDD**
  - **Contaminated wood-based products from Pripyat: Ukraine**
  - **<u>Dispersed nature and low-levels decrease detectability by portal monitors</u>**
- **Smuggling: the deliberate and illicit transport of nuclear or radiological materials**
  - **Usually confined to small volumes**
  - **May be in concentrated forms: purified, enriched, metallic or compounds**
  - **Possibly well-shielded depending on sophistication**
  - **<u>Shielding can greatly impede detection: not necessarily easy to accomplish</u>**

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II. Low-Sigma Alarms and Their Importance[1]

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- **Threat sources may be small (compact) providing few counts/second (cps)**
  - Self-shielding (metals block their own emissions well, U, Pu)
  - Low gamma emission rates (HEU, DU)
  - Low energy gammas easily shielded (HEU)
- **Threat sources may be externally shielded providing few cps**
  - Shielded by cargo
  - Shielded by design
  - Background suppression
- **If we release low-sigma alarms, we may be releasing a threat source**
  - Quite large sources can be hidden from detection due to a combination of the above factors

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II. Low-Sigma Alarms and Their Importance[2]

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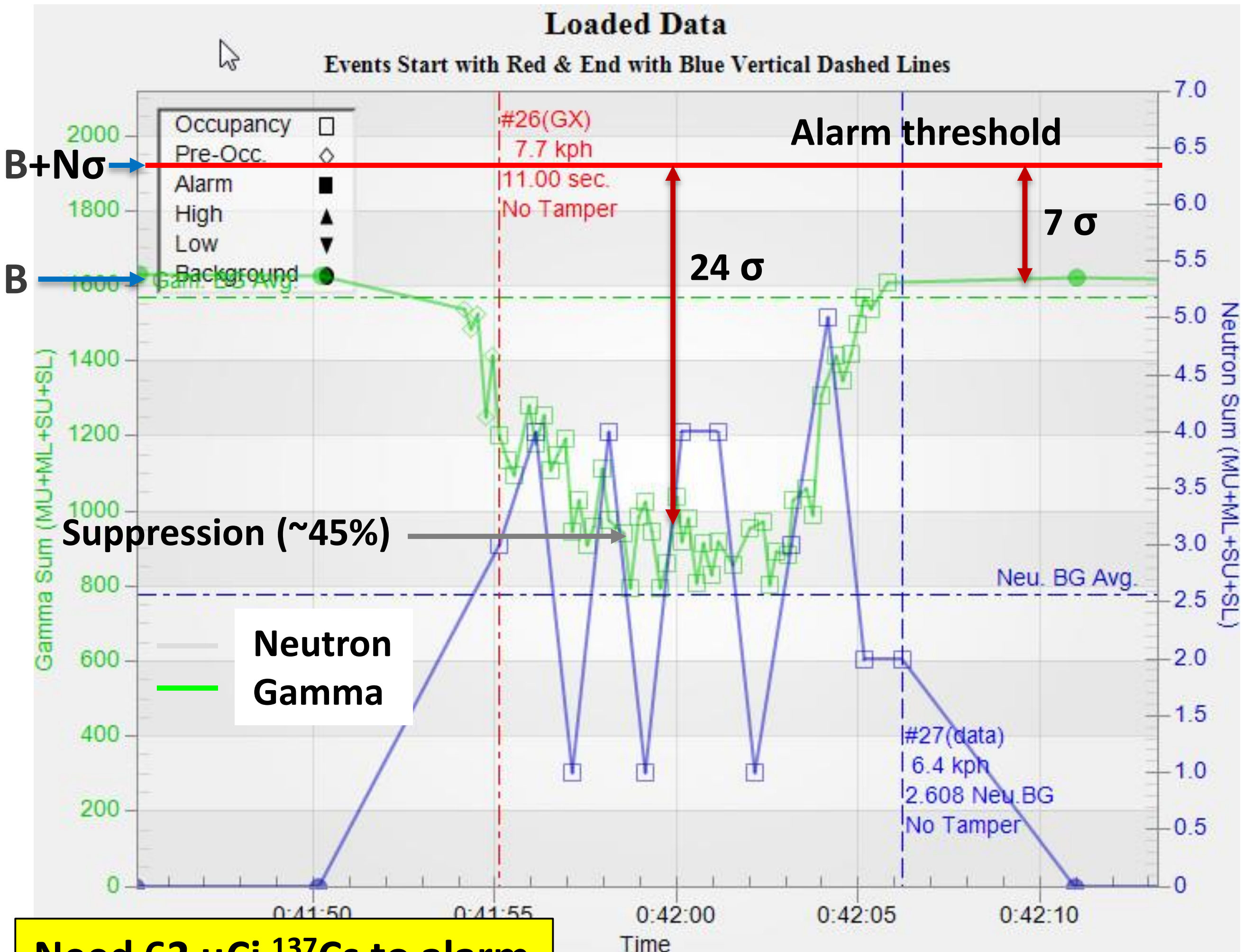

Need 62 μCi ^{137}Cs to alarm

Threshold (Nσ): N = 7.0

Background: B = 1630 cps

Src+bkg rate: S = 950 cps

$\sigma = \sqrt{B} = 40$ cps

SNR = (S-B)/ σ = -17

In this case:

SNR < N σ -> no alarm

Load activity insufficient to exceed the alarm threshold

Suppression greatly reduces sensitivity

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II. Low-Sigma Alarms and Their Importance[2]

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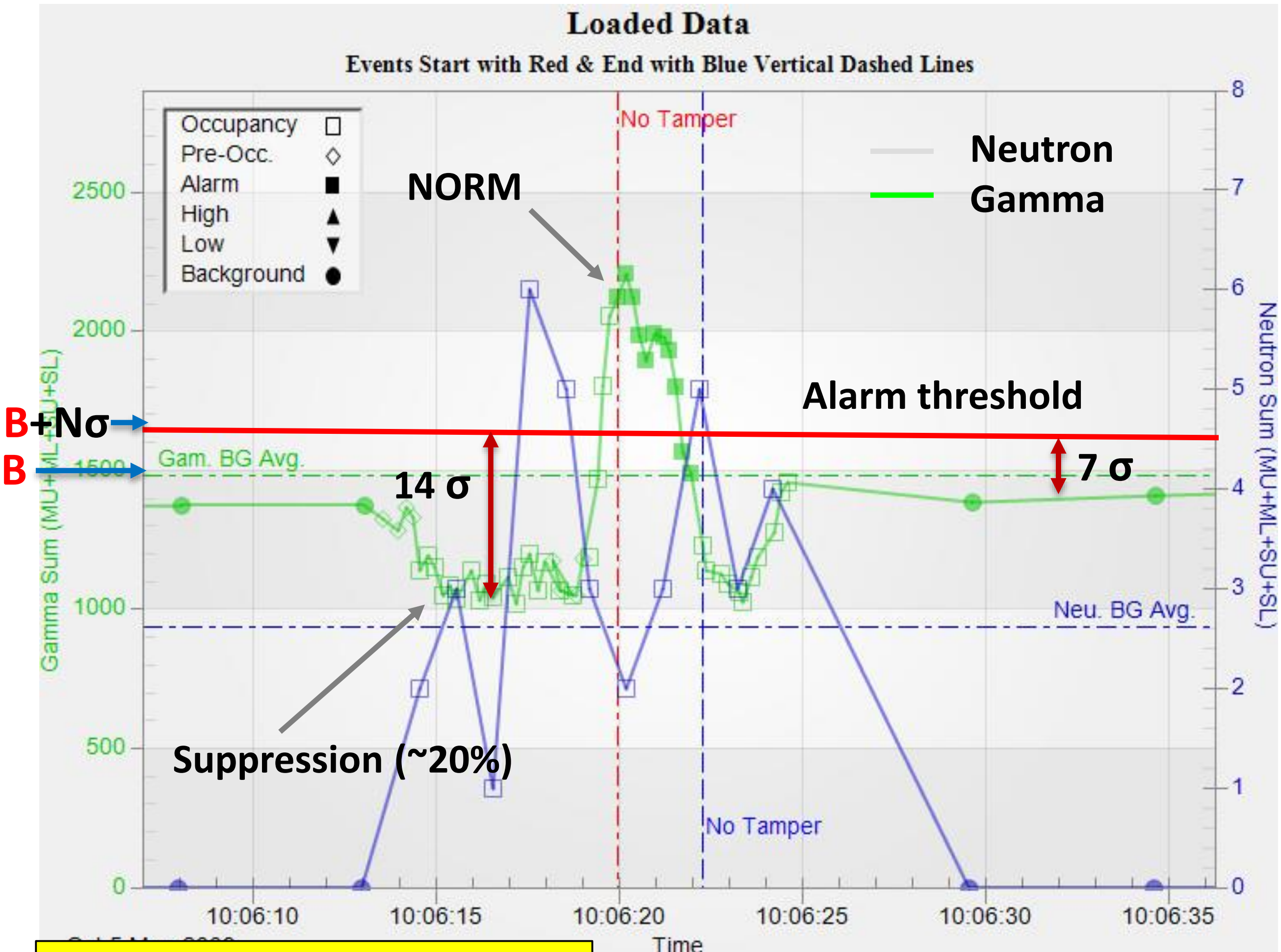

Need 33 µCi ^{137}Cs to alarm

Threshold (Nσ): N = 7.0
Background: B = 1380 cps
Src+bkg rate: S = 2200 cps

σ = √ B = 37 cps

SNR = (S-B)/ σ = 22

In this case:

SNR > N σ -> alarm

Load activity was sufficiently large to exceed suppression well and surpass the alarm threshold

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III. Gamma-Only Alarms and SNM[1]

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		Mass needed to generate 10k n/s
HEU produces very few neutrons[3]		
• 0.0003 n/s/g	spontaneous fission (metal) →	33,000 kg
• 0.0007 n/s/g	alpha, n reactions (oxide)	10,000 kg
• 0.0800 n/s/g	alpha, n reactions (fluoride)	120 kg
• 45,600 γ/s/g (185.7 keV)…but plenty of gamma rays		0.00022 kg
HEU: Gamma-only alarms are most likely here		
WGPu (6% ^{240}Pu) produces many neutrons		
• 61 n/s/g	spontaneous fission (metal) →	160 g
• 44 n/s/g	alpha, n reactions (oxide)	95 g
• 6700 n/s/g	alpha, n reactions (fluoride)	1.5 g
• 145,000 γ/s/g (129.3 keV)…and a lot more		0.07 g
WGPu: Gamma or gamma/neutron alarms likely		

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III. Gamma-Only Alarms and SNM (cont.) [1]

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Spontaneous fission neutron yields:[3]

Table 11-1. Spontaneous fission neutron yields

Isotope A	Number of Protons Z	Number of Neutrons N	Total Half-Life[a]	Spontaneous Fission Half-Life[b] (yr)	Spontaneous Fission Yield[b] (n/s-g)	Spontaneous Fission Multiplicity[b,c] ν	Induced Thermal Fission Multiplicity[c] ν
^{232}Th	90	142	1.41×10^{10} yr	$>1 \times 10^{21}$	$>6 \times 10^{-8}$	2.14	1.9
^{232}U	92	140	71.7 yr	8×10^{13}	1.3	1.71	3.13
^{233}U	92	141	1.59×10^{5} yr	1.2×10^{17}	8.6×10^{-4}	1.76	2.4
^{234}U	92	142	2.45×10^{5} yr	2.1×10^{16}	5.02×10^{-3}	1.81	2.4
^{235}U	92	143	7.04×10^{8} yr	3.5×10^{17}	2.99×10^{-4}	1.86	2.41
^{236}U	92	144	2.34×10^{7} yr	1.95×10^{16}	5.49×10^{-3}	1.91	2.2
^{238}U	92	146	4.47×10^{9} yr	8.20×10^{15}	1.36×10^{-2}	2.01	2.3
^{237}Np	93	144	2.14×10^{6} yr	1.0×10^{18}	1.14×10^{-4}	2.05	2.70
^{238}Pu	94	144	87.74 yr	4.77×10^{10}	2.59×10^{3}	2.21	2.9
^{239}Pu	94	145	2.41×10^{4} yr	5.48×10^{15}	2.18×10^{-2}	2.16	2.88
^{240}Pu	94	146	6.56×10^{3} yr	1.16×10^{11}	1.02×10^{3}	2.16	2.8
^{241}Pu	94	147	14.35 yr	(2.5×10^{15})	(5×10^{-2})	2.25	2.8
^{242}Pu	94	148	3.76×10^{5} yr	6.84×10^{10}	1.72×10^{3}	2.15	2.81
^{241}Am	95	146	433.6 yr	1.05×10^{14}	1.18	3.22	3.09
^{242}Cm	96	146	163 days	6.56×10^{6}	2.10×10^{7}	2.54	3.44
^{244}Cm	96	148	18.1 yr	1.35×10^{7}	1.08×10^{7}	2.72	3.46
^{249}Bk	97	152	320 days	1.90×10^{9}	1.0×10^{5}	3.40	3.7
^{252}Cf	98	154	2.646 yr	85.5	2.34×10^{12}	3.757	4.06

[a]Ref. 1.
[b]Ref. 2. Values in parentheses are from Ref. 3 and have estimated accuracies of two orders of magnitude. Pu-240 fission rate is taken from Refs. 4 and 5.
[c]Ref. 6.

For WGPu metal, ^{240}Pu spontaneous fission dominates neutron emission

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III. Gamma-Only Alarms and SNM (cont.) [1]

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Alpha particle-induced neutron yields:[3]

Table 11-3. (Alpha,n) reaction neutron yields

Isotope A	Total Half-Life[a]	Alpha Decay Half-Life[a]	Alpha Yield[a] (α/s-g)	Average Alpha Energy[a] (MeV)	(α,n) Yield in Oxide[b] (n/s-g)	(α,n) Yield in UF_6/PuF_4[c] (n/s-g)
^{232}Th	1.41×10^{10} yr	1.41×10^{10} yr	4.1×10^{3}	4.00	2.2×10^{-5}	
^{232}U	71.7 yr	71.7 yr	8.0×10^{11}	5.30	1.49×10^{4}	2.6×10^{6}
^{233}U	1.59×10^{5} yr	1.59×10^{5} yr	3.5×10^{8}	4.82	4.8	7.0×10^{2}
^{234}U	2.45×10^{5} yr	2.45×10^{5} yr	2.3×10^{8}	4.76	3.0	5.8×10^{2}
^{235}U	7.04×10^{8} yr	7.04×10^{8} yr	7.9×10^{4}	4.40	7.1×10^{-4}	0.08
^{236}U	2.34×10^{7} yr	2.34×10^{7} yr	2.3×10^{6}	4.48	2.4×10^{-2}	2.9
^{238}U	4.47×10^{9} yr	4.47×10^{9} yr	1.2×10^{4}	4.19	8.3×10^{-5}	0.028
^{237}Np	2.14×10^{6} yr	2.14×10^{6} yr	2.6×10^{7}	4.77	3.4×10^{-1}	
^{238}Pu	87.74 yr	87.74 yr	6.4×10^{11}	5.49	1.34×10^{4}	2.2×10^{6}
^{239}Pu	2.41×10^{4} yr	2.41×10^{4} yr	2.3×10^{9}	5.15	3.81×10^{1}	5.6×10^{3}
^{240}Pu	6.56×10^{3} yr	6.56×10^{3} yr	8.4×10^{9}	5.15	1.41×10^{2}	2.1×10^{4}
^{241}Pu	14.35 yr	5.90×10^{5} yr	9.4×10^{7}	4.89	1.3	1.7×10^{2}
^{242}Pu	3.76×10^{5} yr	3.76×10^{5} yr	1.4×10^{8}	4.90	2.0	2.7×10^{2}
^{241}Am	433.6 yr	433.6 yr	1.3×10^{11}	5.48	2.69×10^{3}	
^{242}Cm	163 days	163 days	1.2×10^{14}	6.10	3.76×10^{6}	
^{244}Cm	18.1 yr	18.1 yr	3.0×10^{12}	5.80	7.73×10^{4}	
^{249}Bk	320 days	6.1×10^{4} yr	8.8×10^{8}	5.40	1.8×10^{1}	
^{252}Cf	2.646 yr	2.731 yr	1.9×10^{13}	6.11	6.0×10^{5}	

[a]Ref. 1.
[b]Ref. 2.
[c]UF_6, Refs. 23 and 24; PuF_4, Ref. 25.

For WGPu oxides and fluorides, ^{239}Pu a, n reactions dominate neutron emission.

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IV. Profile Analysis Pitfalls[1]

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What is *Profile Analysis*? It is the premise that the time-dependent shape (profile) indicates source spatial extent and thus permits the differentiation of threat from non-threat--a flawed premise.

What information is to be acquired through profile analysis? Here are some commonly heard variants; data that permits

- Discrimination between NORM and non-NORM loads
- Discrimination between point-like and distributed loads

Can it do any of these things and is it relevant?

- The short answer is no to both questions
- Non-spectroscopic: no ID capability (EW-energy windowing extremely poor)
- Wide viewing angle: spatial discrimination is poor (currently)
- Some threats are point-like, some have large physical extent

Often this approach is offered as a possible means of reducing secondary referral rates

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IV. Profile Analysis Pitfalls[1]

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The risk of using profile analysis to reduce secondary screening volume:

- Improper dismissal of a threat (very high probability)

Why is that expected?

- Point and distributed source profiles are indistinguishable
- Profiles produced by 6 m NORM loads indistinguishable from point source profiles
- Two point sources cannot be spatially resolved if less than 6 m apart with current collimator design
- Two point sources at 4 m or less separation produce profiles that are indistinguishable from a single point source

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IV. Profile Analysis: Longitudinal Point Source Spatial Resolution[1]

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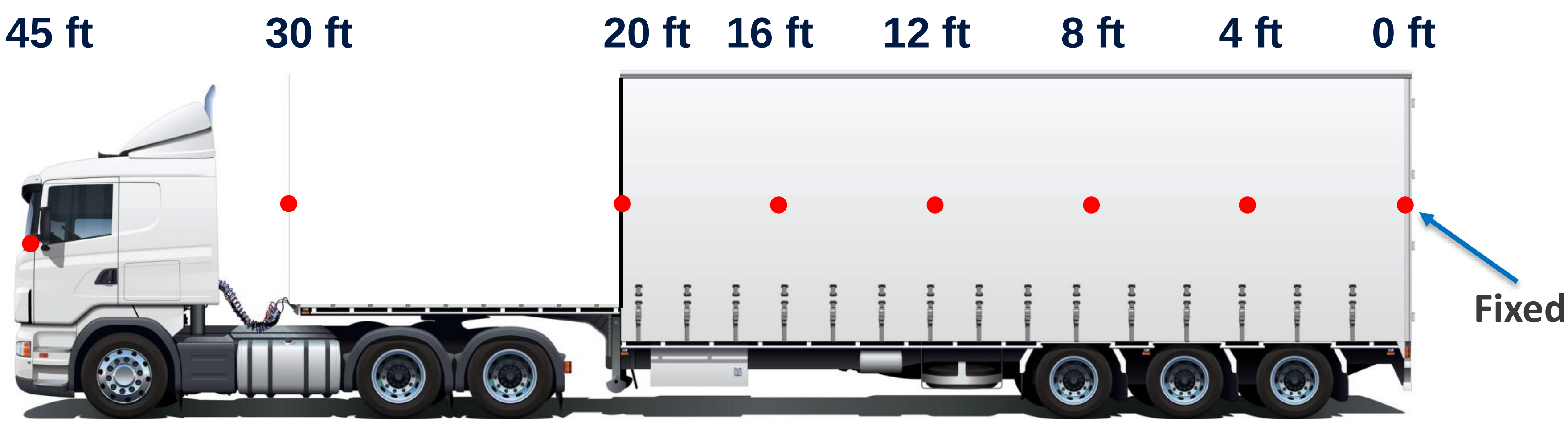
What is the closest distance between <u>two point sources</u> such that they may be resolved spatially along the direction of travel?

Cs-137 sources (•): 37.8 µCi and 46.8 µCi

Uncollimated VM-250 RPM

Container is otherwise empty



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IV. Profile Analysis: Longitudinal Point Source Spatial Resolution[1]

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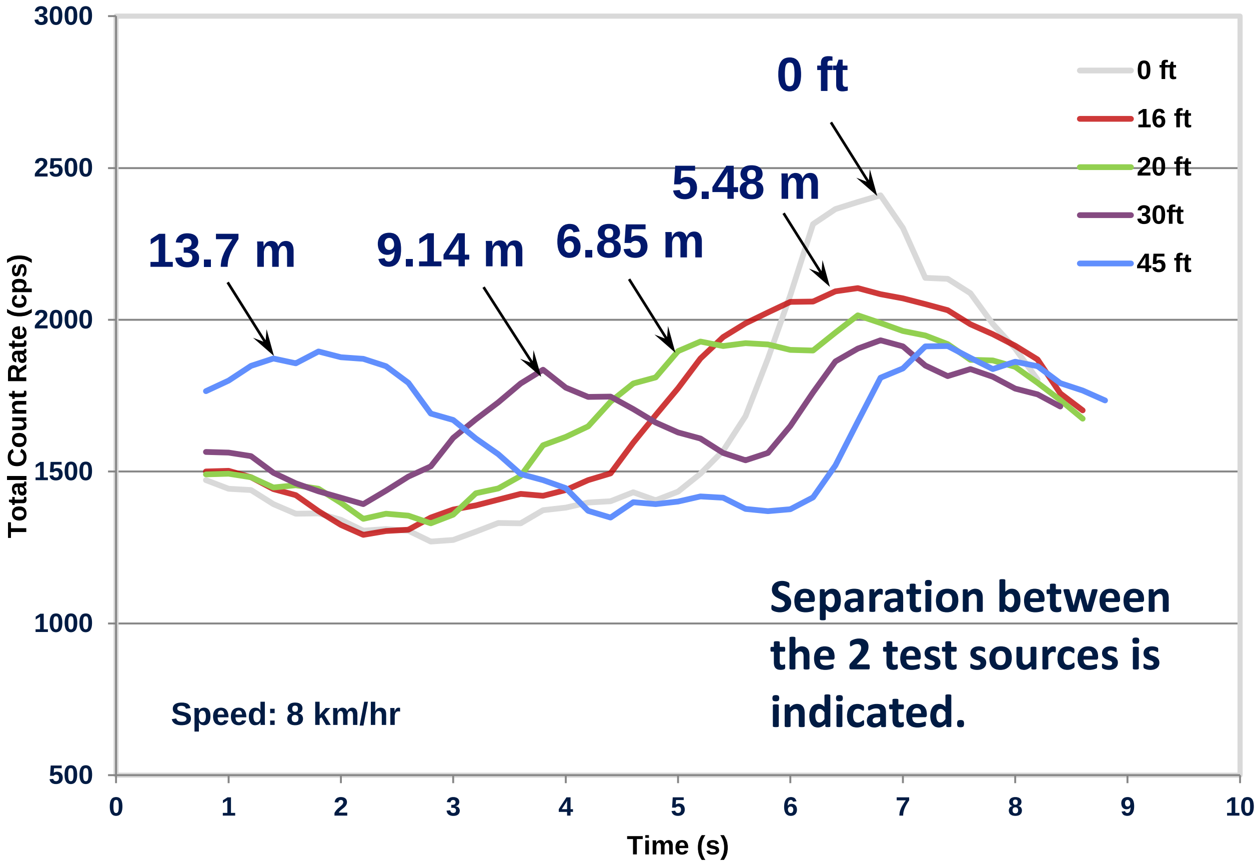
Note: There is interest in interdicting point-like and spatially distributed sources.

Real threats may have significant spatial extent; i.e., they may not be point-like.



Minimum source separation distance to spatially resolve (un-collimated): 7 to 9 m

With standard collimator, this improves by about a factor of 2

Could redesign collimator to improve resolution but cost is detection sensitivity loss

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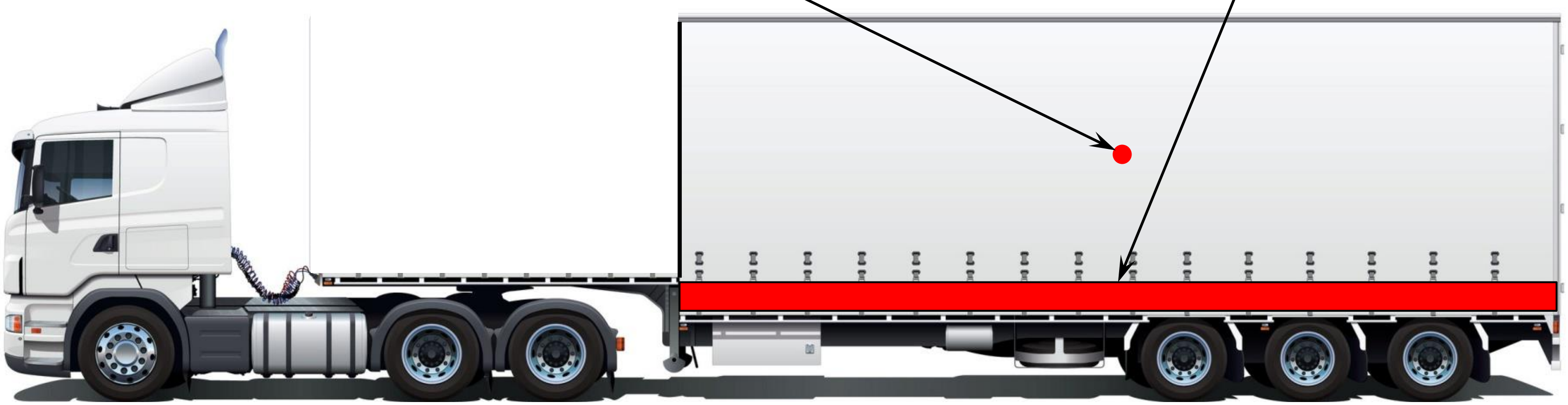
IV. Profile Analysis: Point and Distributed Source Responses[1]

Can the gamma detection profiles be distinguished from one another?

Uniformly distributed NORM (U and Th decay chain)

37.8 µCi Cs-137



IV. Profile Analysis: Point and Distributed Source Responses[1]

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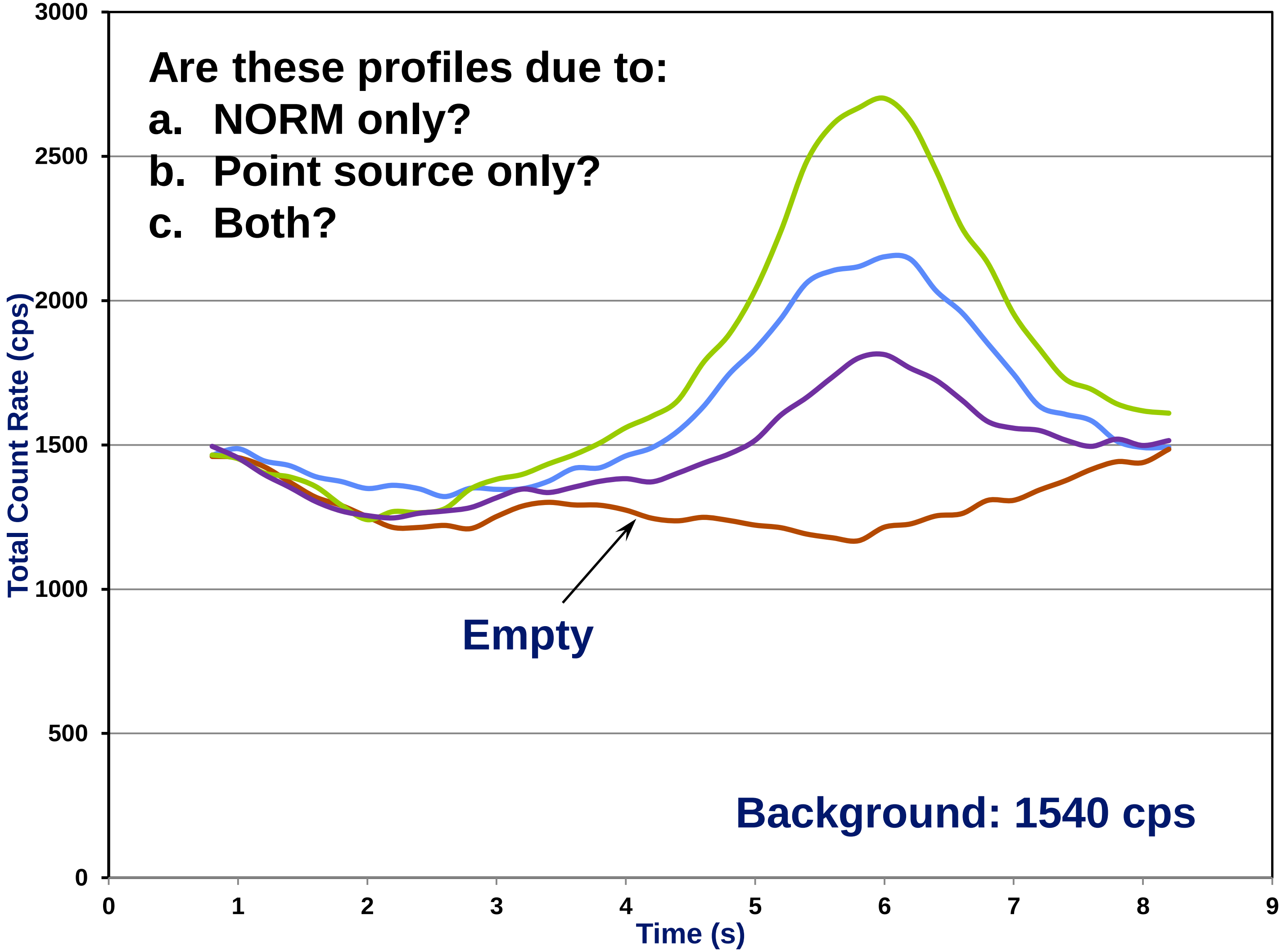

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IV. Profile Analysis: Point and Distributed Source Responses[1]

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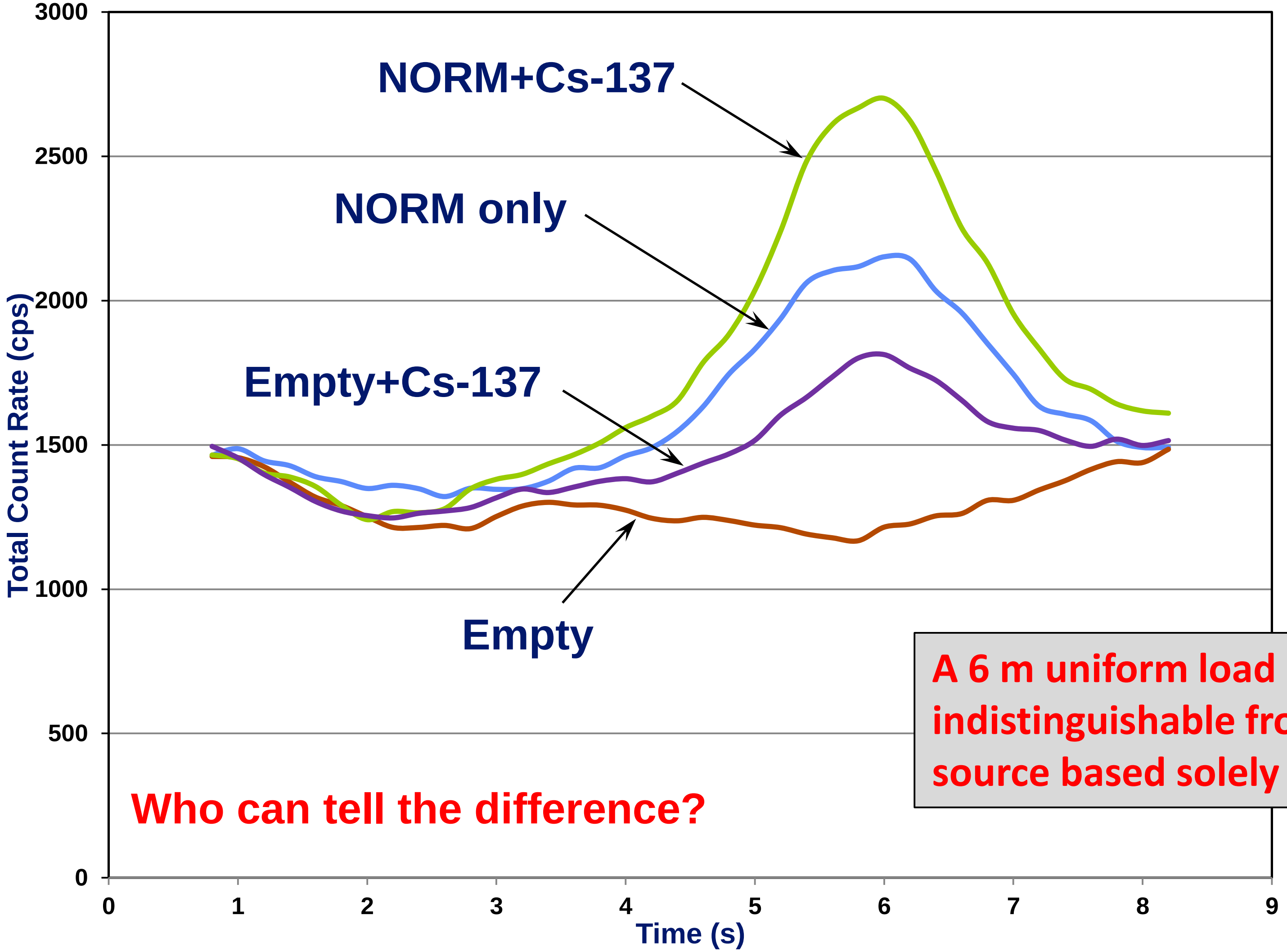

A 6 m uniform load of NORM is indistinguishable from a point source based solely on its profile.

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V. Energy Windowing-Some Comments[1]

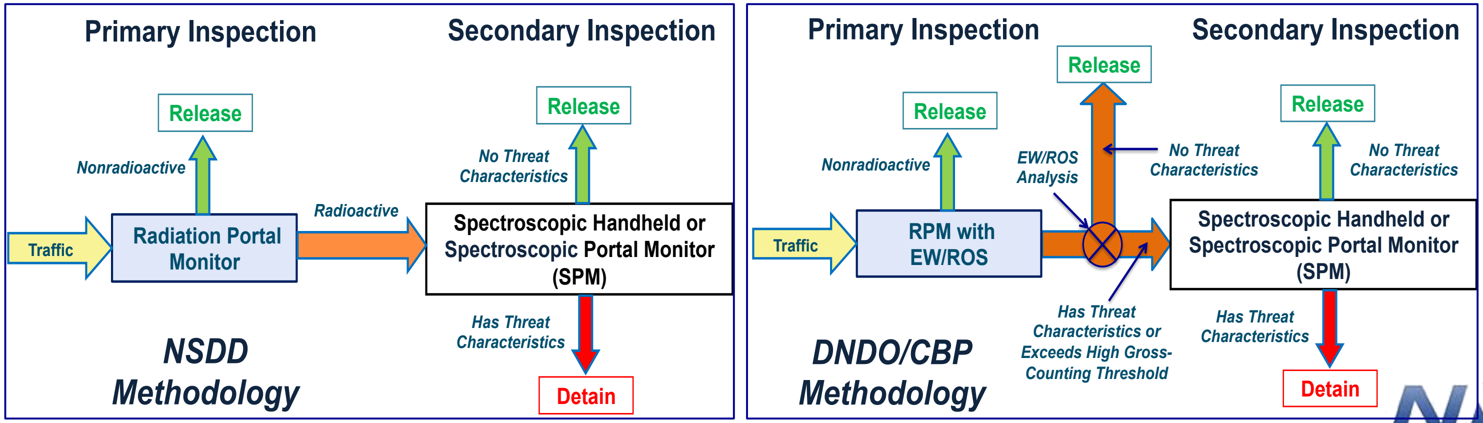
What problem does EW and the DNDO Revised Operational Standards address?

Nuisance Alarms

- Real primary alarms caused by benign sources – NORM and other isotopes in cargo
- Nuisance alarms comprise most containers/vehicles sent to secondary
- Nuisance alarm rate (NAR) overwhelms secondary screening capabilities at Customs and Border Patrol (CPB) and NSDD sites

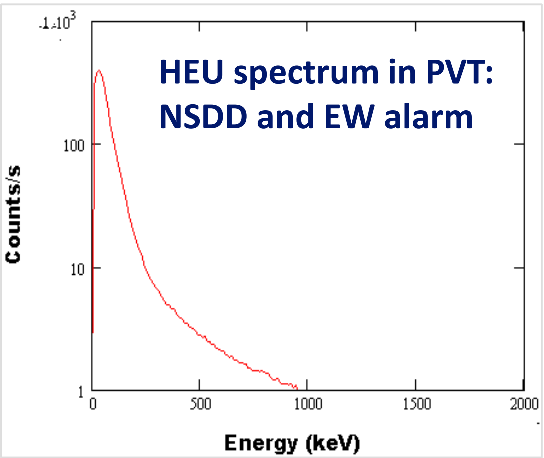
Two Solutions

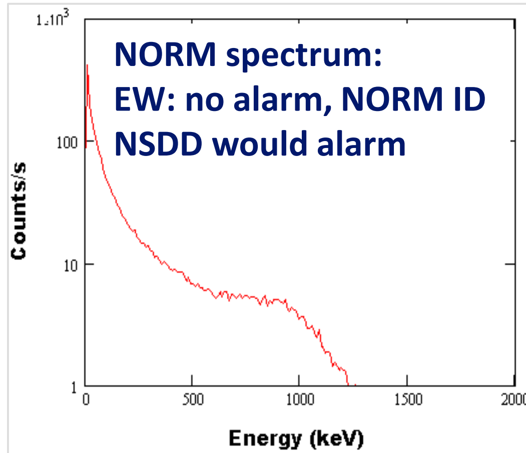
- CBP: Use energy windowing on primary detector spectra to adjudicate some alarms and release, reducing rate of referral to secondary
- NSDD: Improve secondary screening equipment to increase secondary throughput

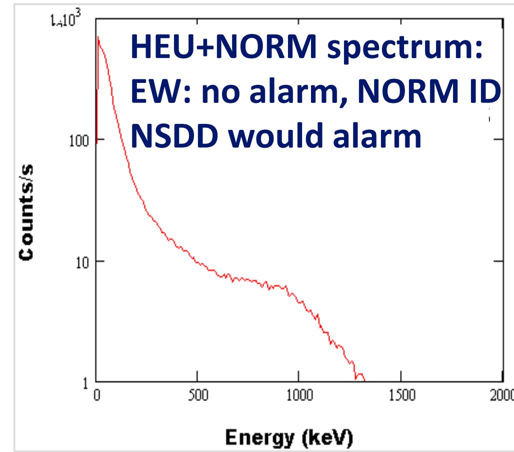


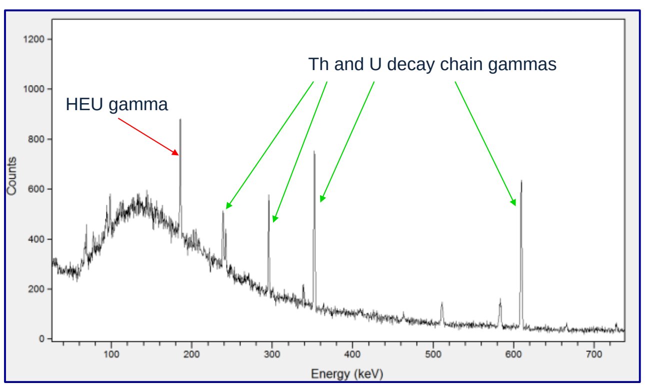
V. Energy Windowing-Some Comments[1]

Container producing combined spectrum from threat and NORM would be released

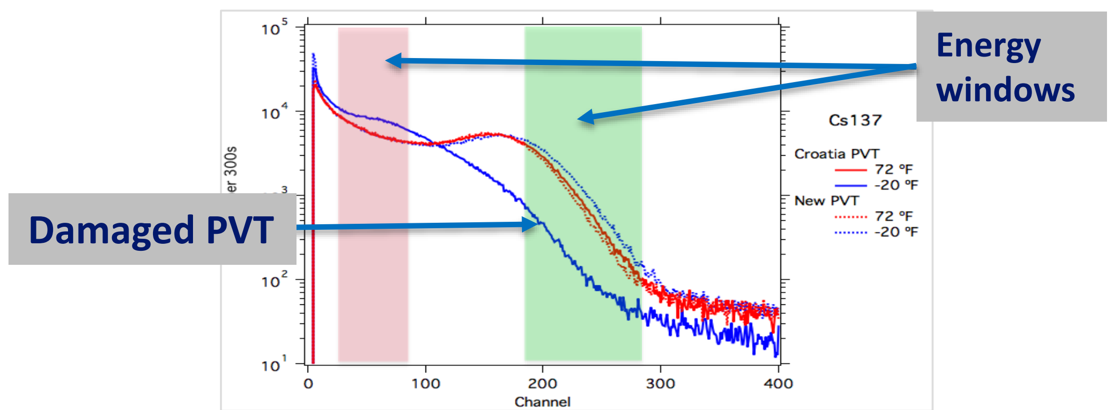








High resolution secondary detectors would have identified HEU



Gain shift (solid blue trace) would shift "spectrum" out of optimized EWs

VI. Neutron Alarms in Primary Inspection[4]

Neutron alarms-various causes:

- **Case 1: Cosmic ray-induced alarms**
- **Case 2: Noise induced (PMFX pickoff box, connectors)**
- **Case 3: Percussively-induced, keyboard-induced alarms**
- **Case 4: Statistical false alarm-short background evaluation time**
- **Case 5: Real neutron source**
- **Case 6: Low LLD on neutron detectors**

VI. Neutron Alarm Event: Case 1

Cosmic-ray-induced neutron alarm

- Location 1, L110: October 10, 2009 16:34:30 pm
- Train parked between pillars for ~1.75 hours
- Two isolated events occurred in a single occupancy
- One caused an alarmed, one did not
- Die-away time for neutron detection in these monitors ~50 μs

Defining characteristics:

1. Short duration-much less than one time interval (1 s)
2. No tamper indicating strings
3. No discernible time-correlated gamma signal
4. Time-correlated over two or more detectors
5. Moderate signal strength: significantly higher than background

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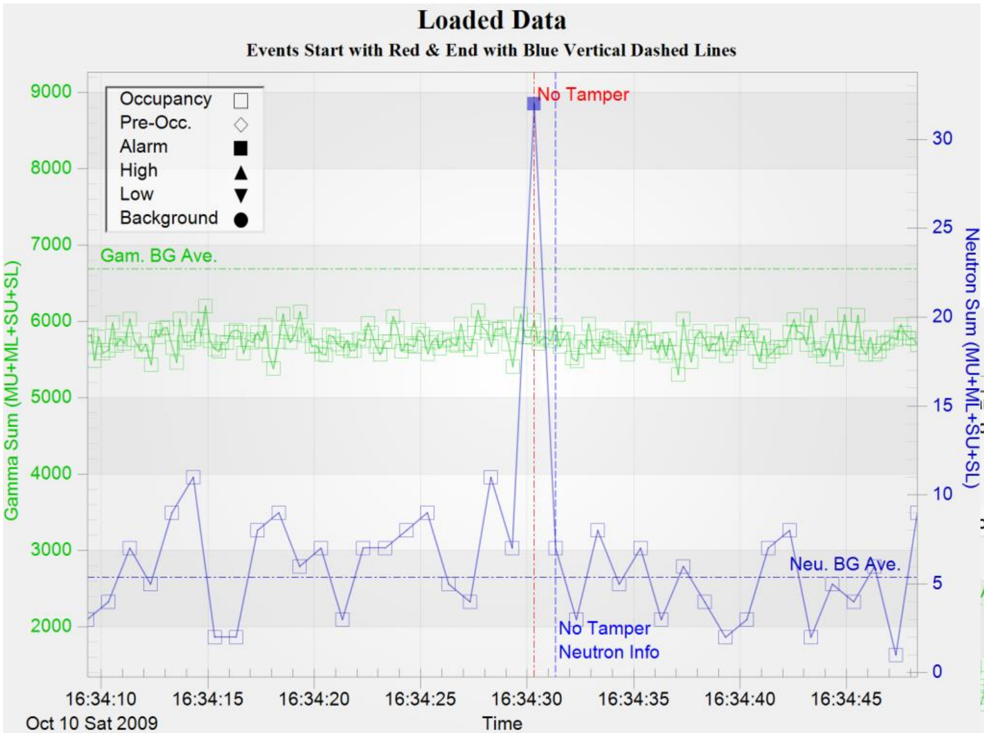
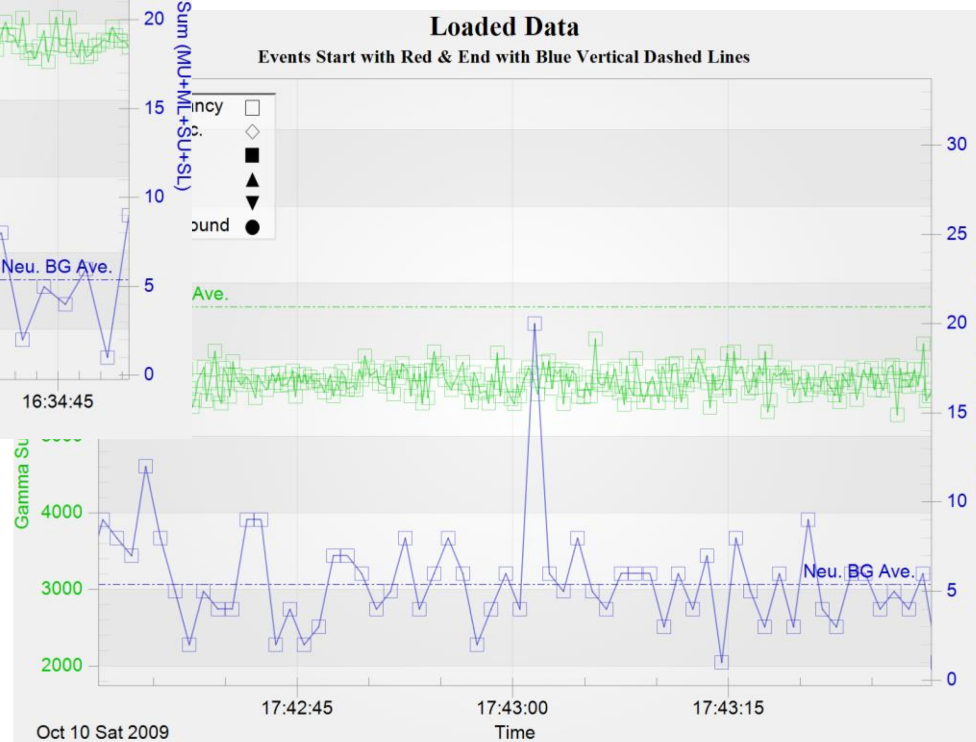
VI. Neutron Alarm Event: Case 1



Signal above background in all 4 detectors simultaneously

NA,000008,000010,000007,000007,16-34-30.323
GX,000027,005858,000000,000000,18-04-59.653



Signal above background in 2 or 3 detectors simultaneously

NS,000004,000008,000007,000001,17-43-01.530
GX,000027,005858,000000,000000,18-04-59.653

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VI. Neutron Alarm Event: Case 1

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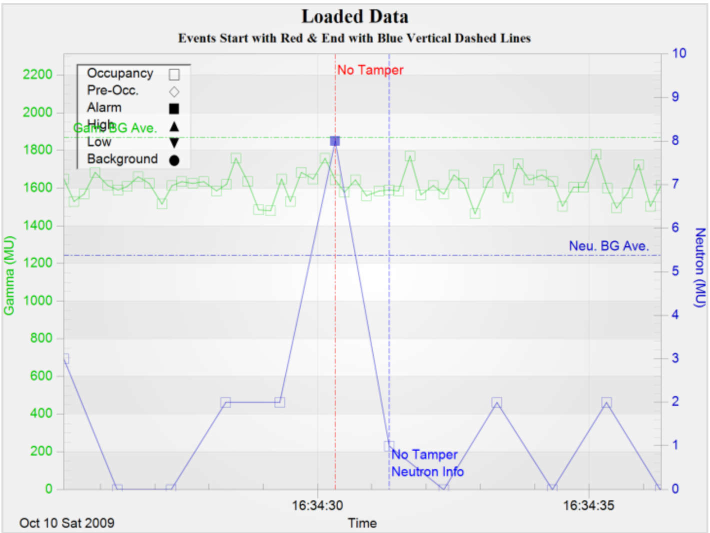

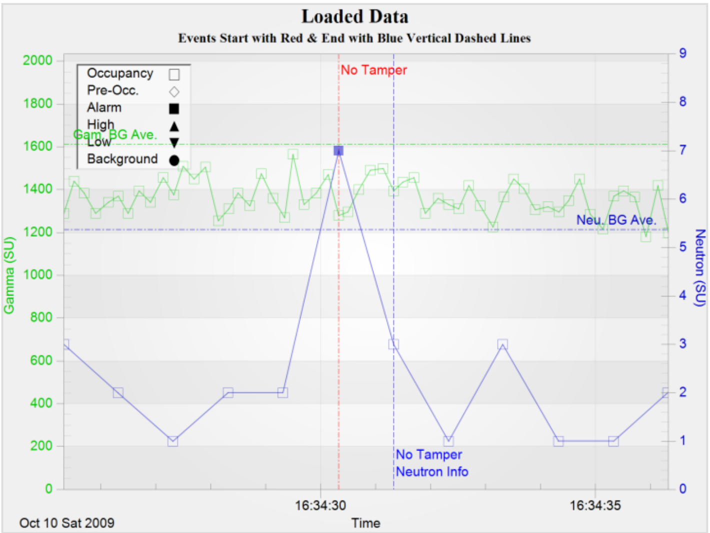

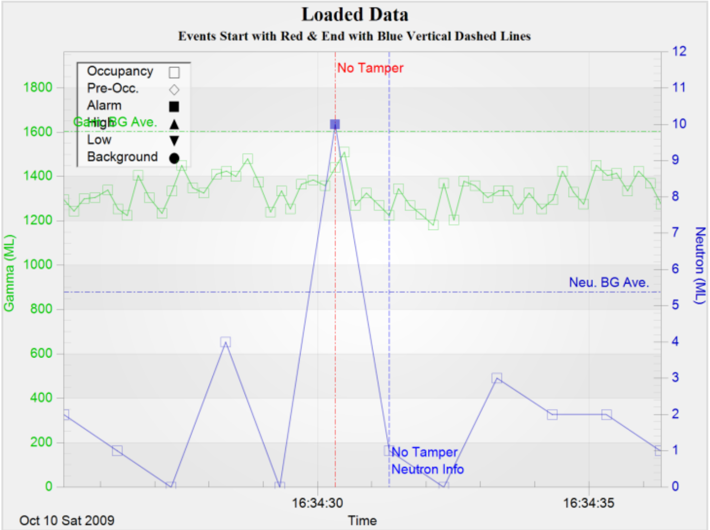

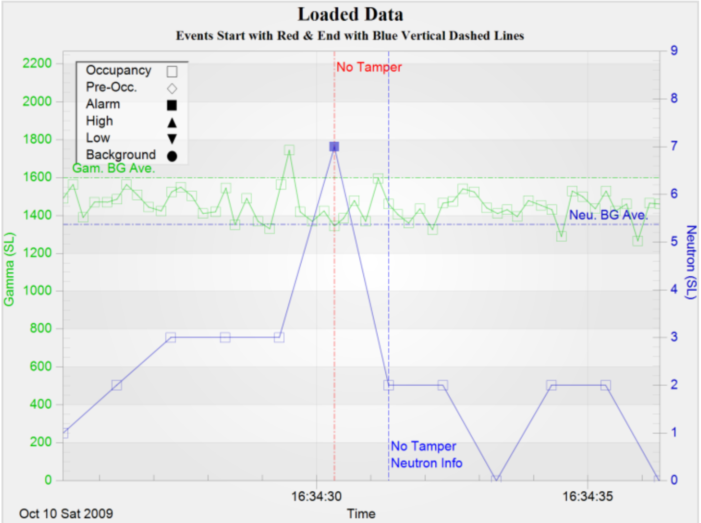

Time-correlated across all four neutron detectors

No discernible gamma signal

All < 1 second in duration

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VI. Neutron Alarm Event: Case 2

Noise-Induced Neutron Alarms

- Location 2, L005: September 22, 2010 (TM as VM application)
- Unusually high neutron alarm rate ~1 in 500 occupancies
- Expect less than 1 in 10,000 occupancies

- Defining characteristics:
  1. May be one or more time intervals (1-3 s)
  2. No tamper indicating strings
  3. No discernible time-correlated gamma signal
  4. Usually not isolated to one detector-both detectors in one pillar
  5. Not apparent from background averages
  6. Moderate signal strength: significantly higher than background

VI. Neutron Alarm Event: Case 2

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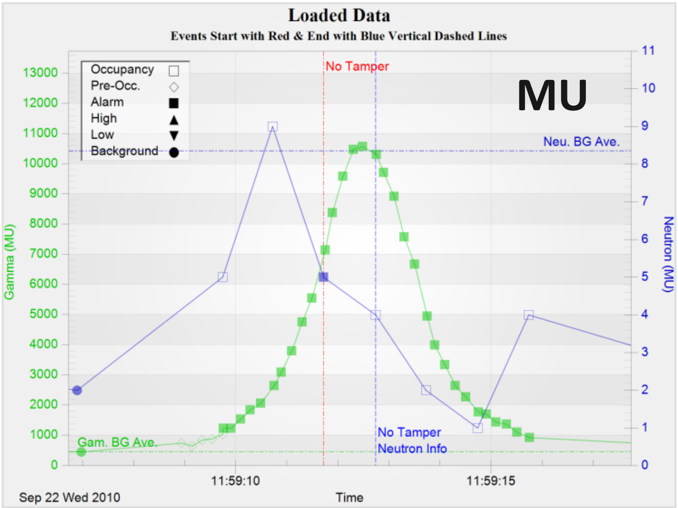
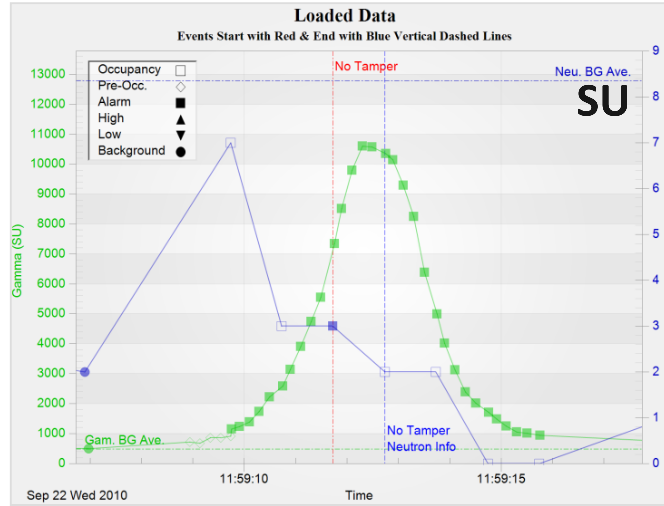
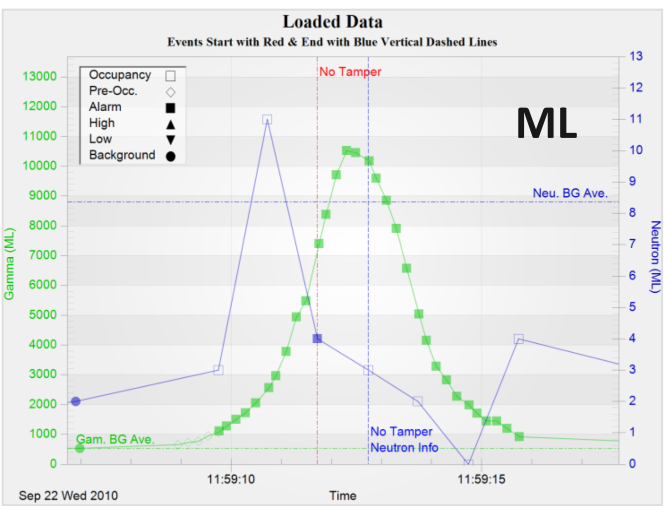
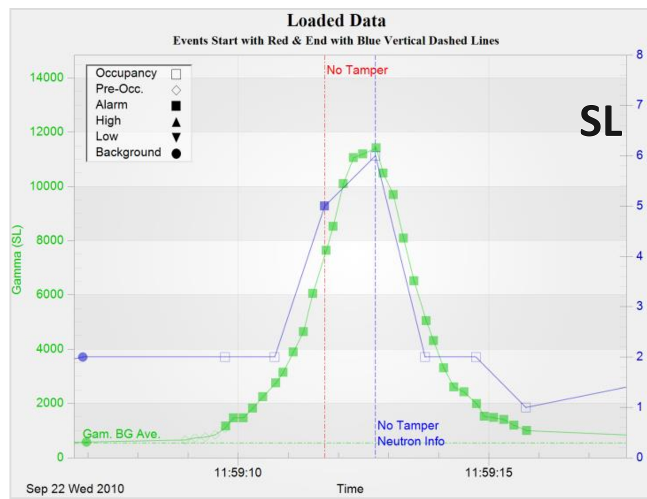




Simultaneous neutron peak

These are not time correlated





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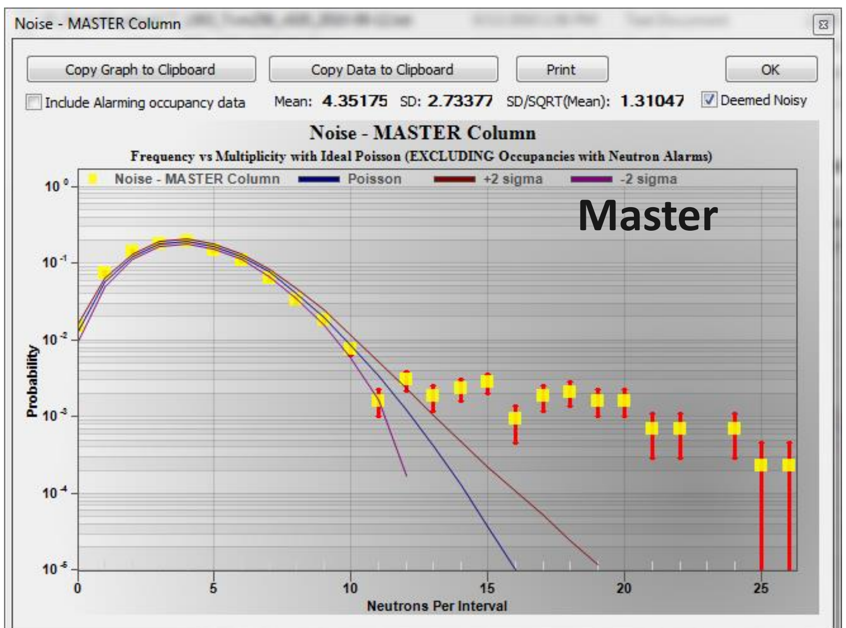
VI. Neutron Alarm Event: Case 2

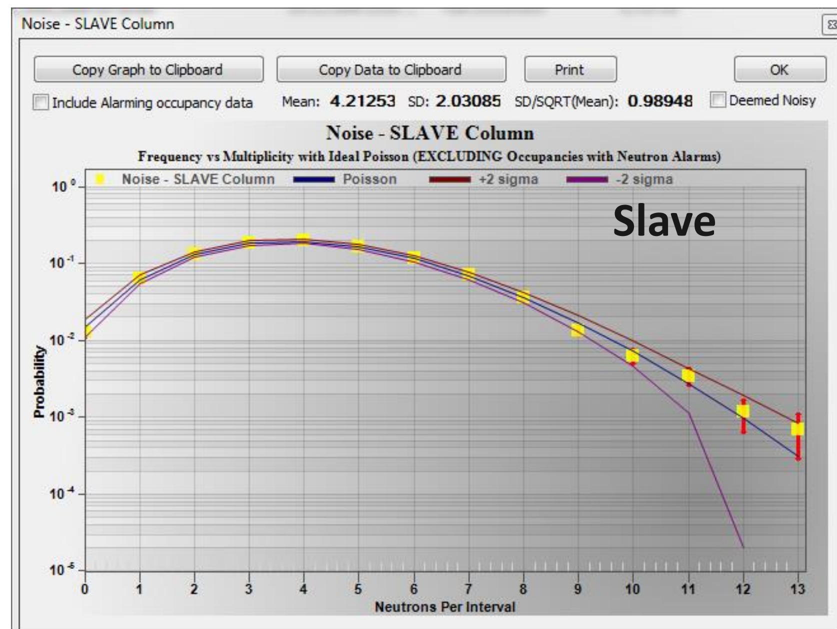
Neutron data should exhibit a Poisson frequency distribution

- **Blue line: Poisson distribution with same mean**
- **Purple lines: 2σ above and below ideal distribution**
- **Yellow points: daily file data ± σ (NS string data)**

Master pillar shows clear indications of a noise problem



Slave pillar looks fine but may also have a slight noise problem



VI. Neutron Alarm Event: Case 2

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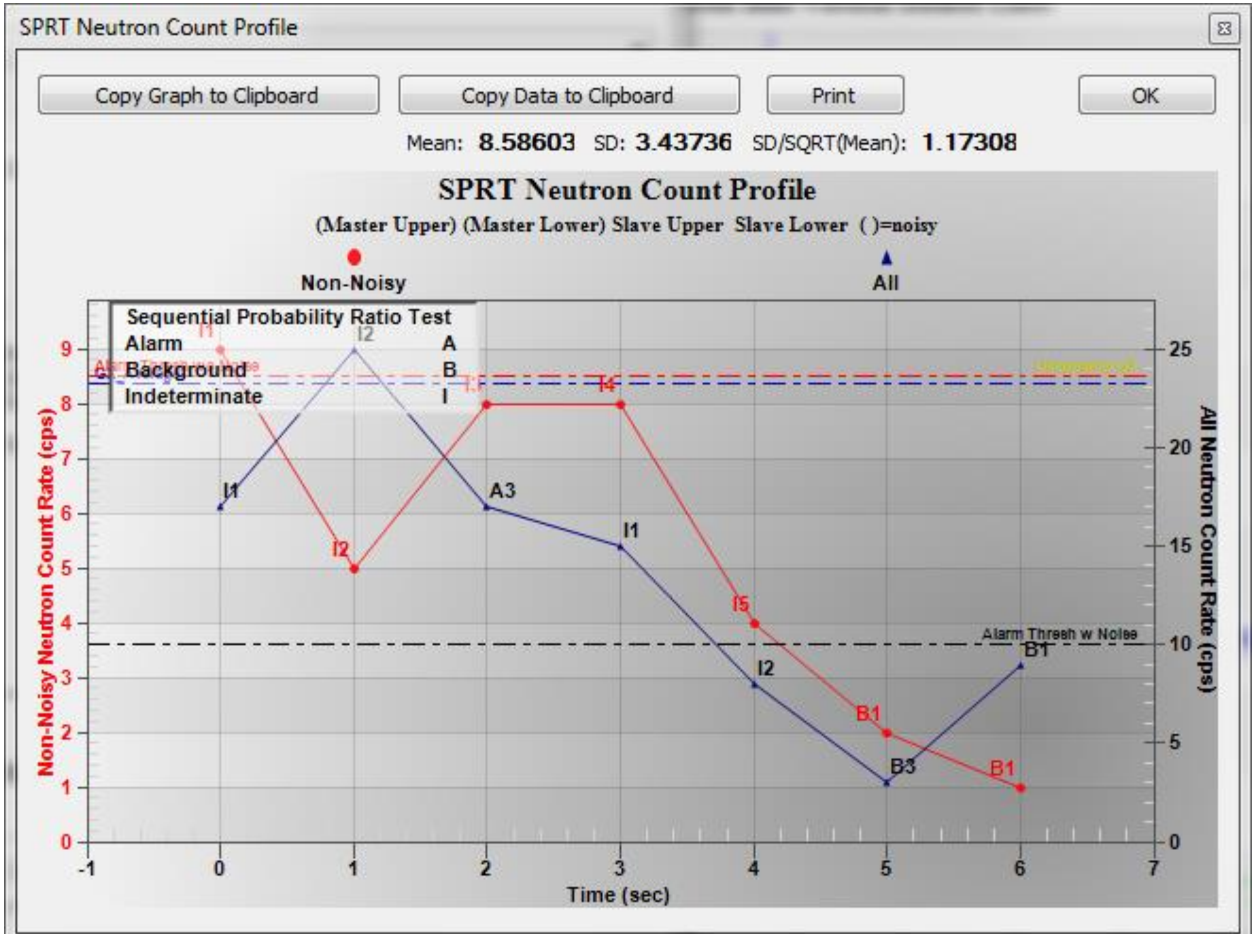

I = indeterminate
B = background
A = alarm

Look for an "A" in the replayed non-noisy data (red line)

If there is no "A", it's probably noise

Run neutron alarm algorithm with all data (blue) and without noisy data (red).

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VI. Neutron Alarm Event: Case 3

Noise induced by changing monitor settings

- Location 3, L109: October 8, 2009, 12:50:00 pm (2 such events that day)
- Personnel were in port changing RPM parameter settings
- Upon exiting control menu-noise spike induced in signal circuitry

Defining characteristics:

1. Short duration--less than one time interval (200 ms)
2. Event enclosed by tamper indicating strings
3. Typically very large signal magnitude
4. Often time-correlated gamma-neutron signal
5. Output of monitor settings may show change

VI. Neutron Alarm Event: Case 3

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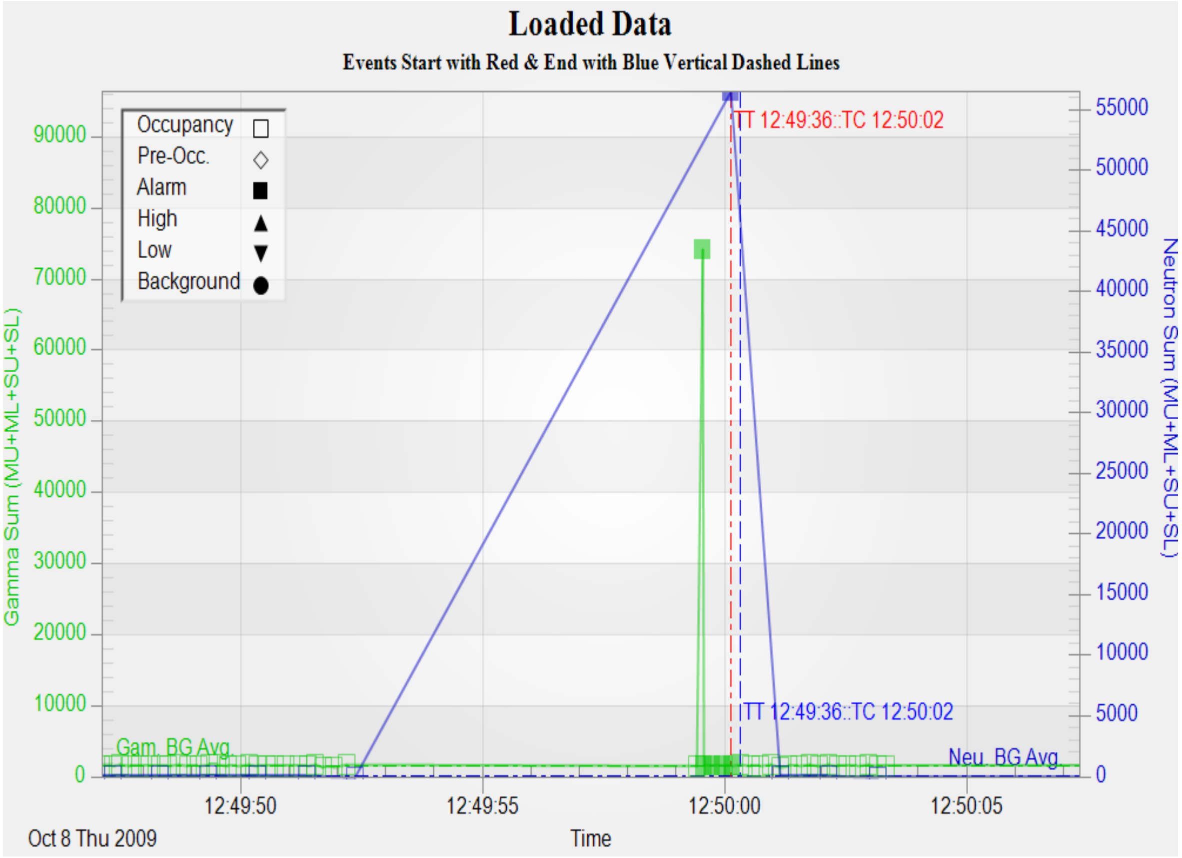
SG1,002000,000068,05,10,07.0,P,23-59-41.695
SG2,1111,0.069,0.455,00,1010,A,23-59-41.695
SG3,0.069,0.455,020,000,1.10.1,23-59-41.710
SN1,000050,05,0004,1200,02,120,23-59-41.726
SN2,0.504,5.040,0.504,5.040,PP,23-59-41.726

← Previous day's monitor settings

Data stream on day of alarm

GB,000374,000348,000389,000404,12-49-35.799
TT,000000,000000,000000,000000,12-49-35.986
SP,0.0459,14.854,023.91,000000,12-49-36.345
NS,000002,000000,000003,000001,12-49-36.564
...
SG1,002000,000068,05,10,05.0,P,12-49-59.423
SG2,1111,0.069,0.455,00,1010,A,12-49-59.454
SG3,0.069,0.455,020,000,1.10.1,12-49-59.454
SN1,000050,05,0004,1200,02,120,12-49-59.454
SN2,0.504,5.040,0.504,5.040,PP,12-49-59.532
GA,000255,-00001,014592,000000,12-49-59.548
GA,000071,000078,000084,000073,12-49-59.564
GA,000072,000069,000092,000081,12-49-59.735
GA,000078,000075,000091,000074,12-49-59.954
NA,016386,019968,000001,020224,12-50-00.126
...
GS,000062,000071,000087,000083,12-50-01.954
TC,111111,111111,111111,111111,12-50-01.970
NS,000000,000000,000002,000001,12-50-02.142



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VI. Neutron Alarm Event: Case 4

Real Neutron Source

- Location 4, L001: September 14, 2010
- Combination gamma and neutron alarm

Defining characteristics:

1. Above background more than 1 s (unless high speed ~50 kph)
2. Shape generally rises and falls as source passes; subject to fluctuation
3. Time-correlated gamma and neutron signals (gammas may be shielded)
4. Gamma and neutron signal in multiple detectors
5. No tamper indicating strings

VI. Neutron Alarm Event: Case 4

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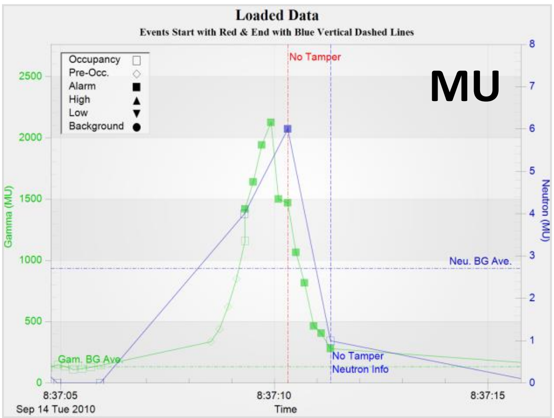
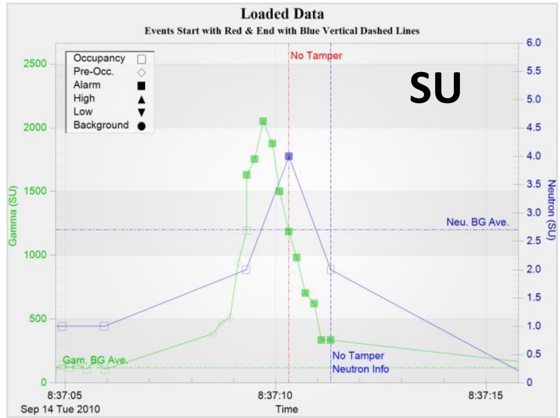
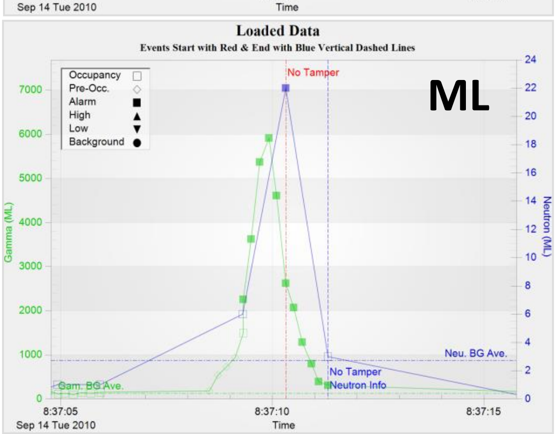
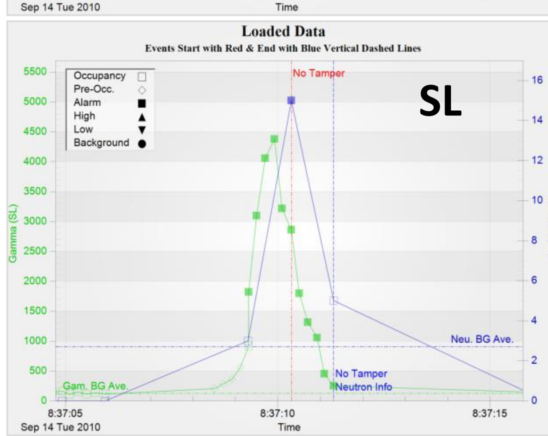


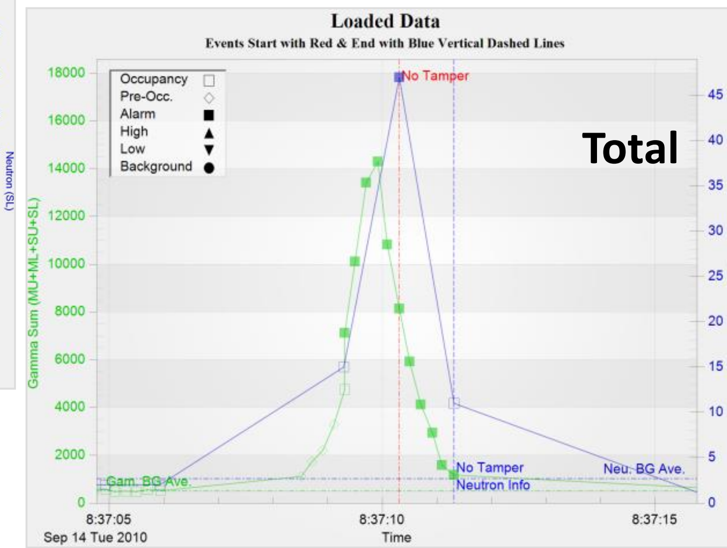


Neutron data: every 1000 ms
Gamma data: every 200 ms

Neutron peak delayed by 500 ms
Gamma peak delayed by 100 ms







Neutron and gamma maxima above occur simultaneously

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VI. Neutron Alarm Event: Case 4

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Source location from monitor center

From neutron data:
0.32 m left
-1.67 m down
21.0 ± 5.3 µCi ^{252}Cf equivalent

From gamma data:*
0.14 m left
-1.33 m down
770 ± 13 µCi ^{137}Cs equivalent

Source is ~35 in. above pavement and 1/3 of a vehicle length from the front. This appears to be consistent with the dash board height and position.

Calculations do not consider shielding

Source locations are referenced to the coordinate system shown in the above picture.

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VI. Neutron Alarm Event: Case 5

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Statistical Neutron Alarm

- Location 5, L003: September 12, 2010
- Neutron only alarm

Defining characteristics:

1. Neutron background before occupancy unusually low compared with the current daily average
2. No time-correlated neutron signal between the four channels
3. No time-correlated gamma signal (with neutron channels, each other)
4. No tamper indicating strings
5. No apparent noise

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VI. Neutron Alarm Event: Case 5

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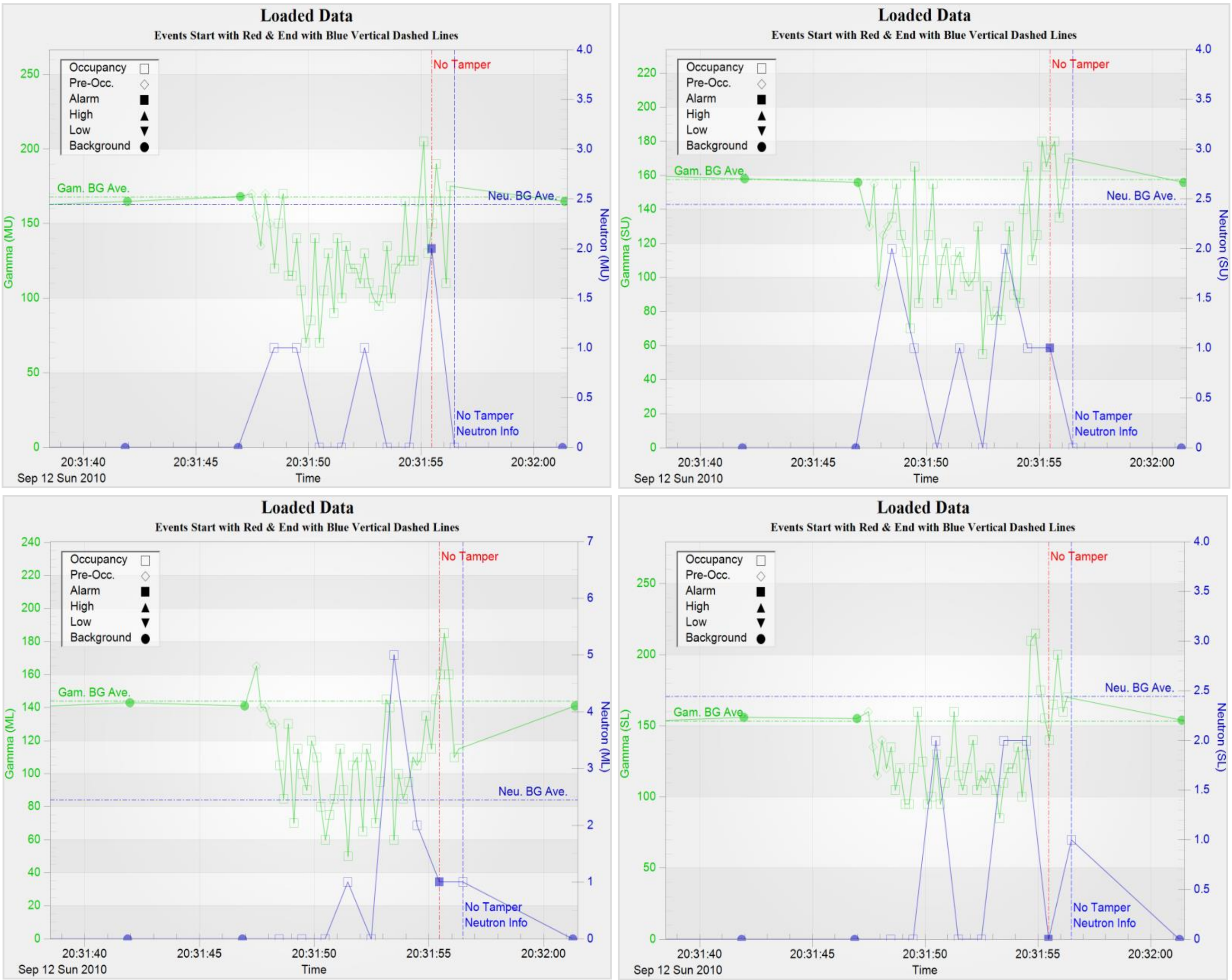

Average neutron background: 2.443 nps

Background before this occupancy: 1.850 nps

<5% chance of having <1.850 nps average for daily mean of 2.443 nps

Had <u>one</u> more neutron been detected during the 20-s background averaging period, this occupancy would not have alarmed

Neutron background normally is integrated over <u>120 s</u> to avoid this very thing.

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VI. Neutron Alarm Event: Case 6

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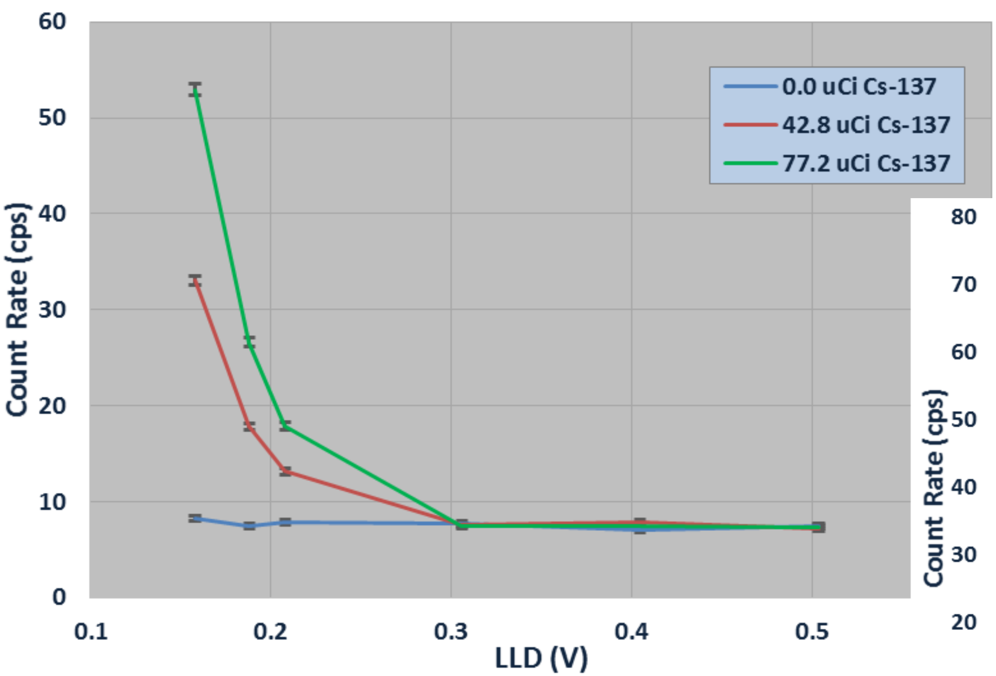
Low LLD on neutron detectors

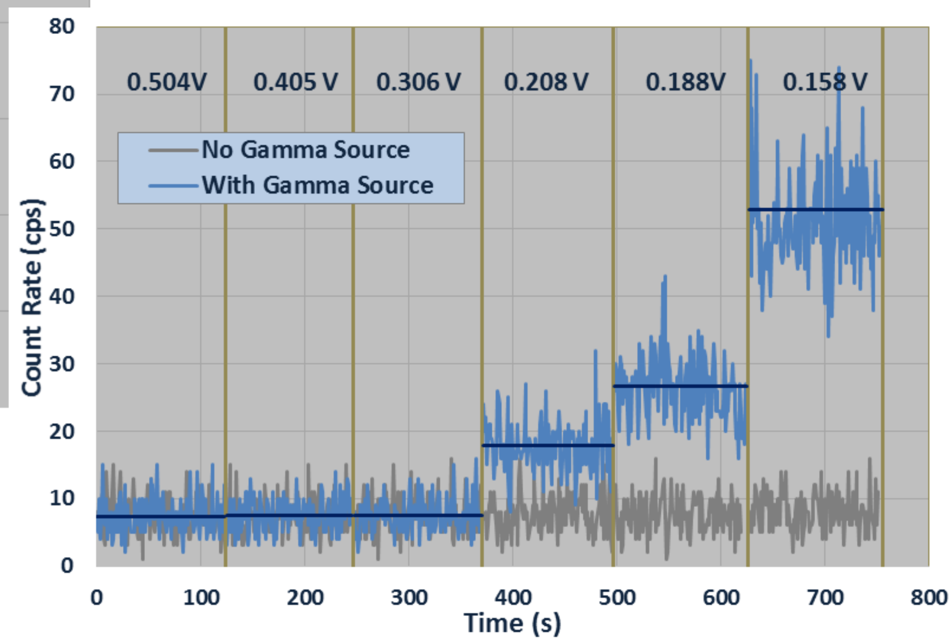
- No gamma source: normal neutron count rate down to LLD voltage of 0.158 V

  With gamma source: spurious neutron counts from gamma sensitivity in tube

Count Rate vs LLD Voltage



Count Rate vs Time



With 77.2 ∓Ci ^{137}Cs source in direct contact with neutron detector module face (HDPE- high density polyethylene)

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VI. Neutron Alarm Event: Case 6

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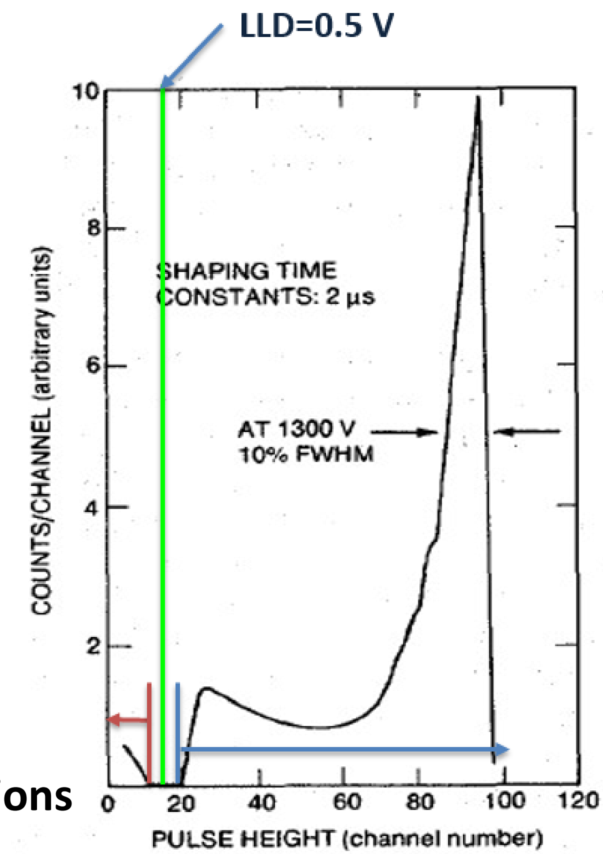
Pulse Height Spectrum-He-3 Neutron Detector



Gamma interactions and noise

Neutron interactions

LLD is too high: lose neutron detection sensitivity

LLD is too low: induce gamma sensitivity

n + ^{3}He → ^{3}H + ^{1}H (~765 keV)

^{3}He (4 atm) + Ar (2 atm), 2.5 cm diameter

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References

[1] LA-UR-17-25397, Discussion Topics for Meeting with Spanish Partners, John Rennie, July 2017.

[2] LA-UR-16-24543 Primary Inspection Detectors, John Rennie, July 2017

[3] LA-UR-90-732 PANDA Manual

[4] LA-UR-16-24400 Primary Inspection Analysis, John Rennie, July 2017.

Extra: Detection System Purpose[2]

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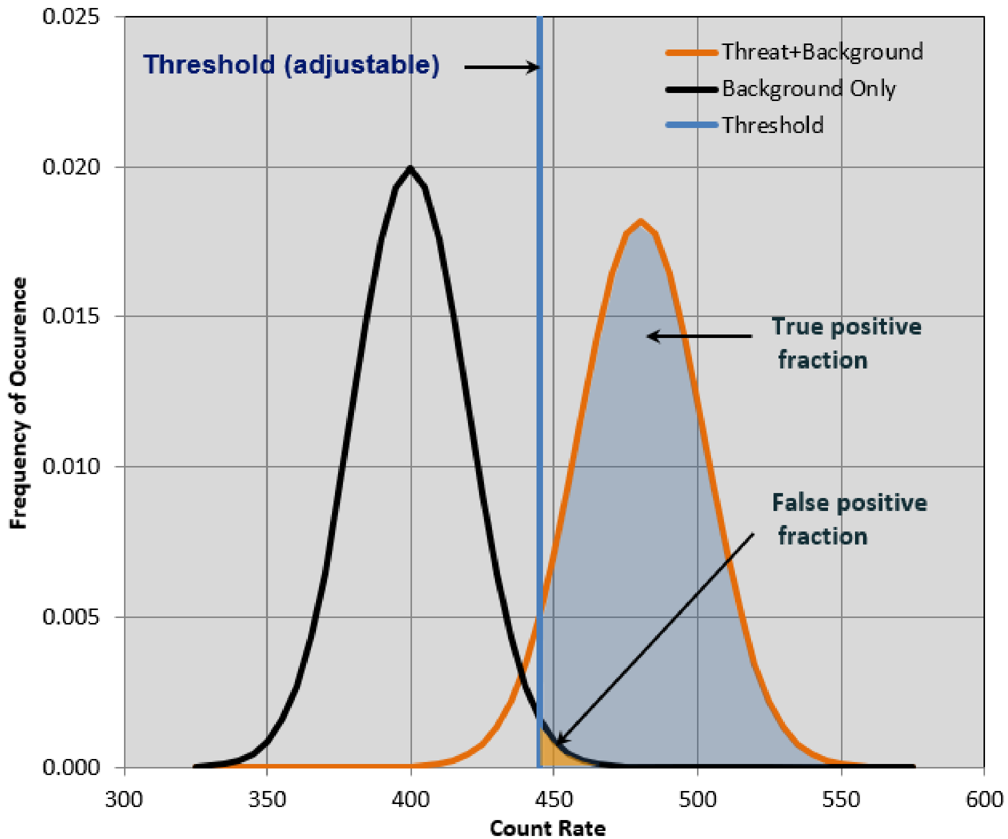

Purpose: Distinguish background from threat + background.

Adjusting the alarm threshold varies the ***False Positive Fraction*** (FPF) and the ***True Positive Fraction*** (TPF). The tradeoff is an operating characteristics (OC) curve.

If the distributions are well separated (large threat), a low FPF and a high TPF can be achieved (desirable).

If the distributions are <u>not</u> well separated (small threat), a high FPF often results (not desirable).

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Extra: Operating Characteristic (OC) Curve[2]

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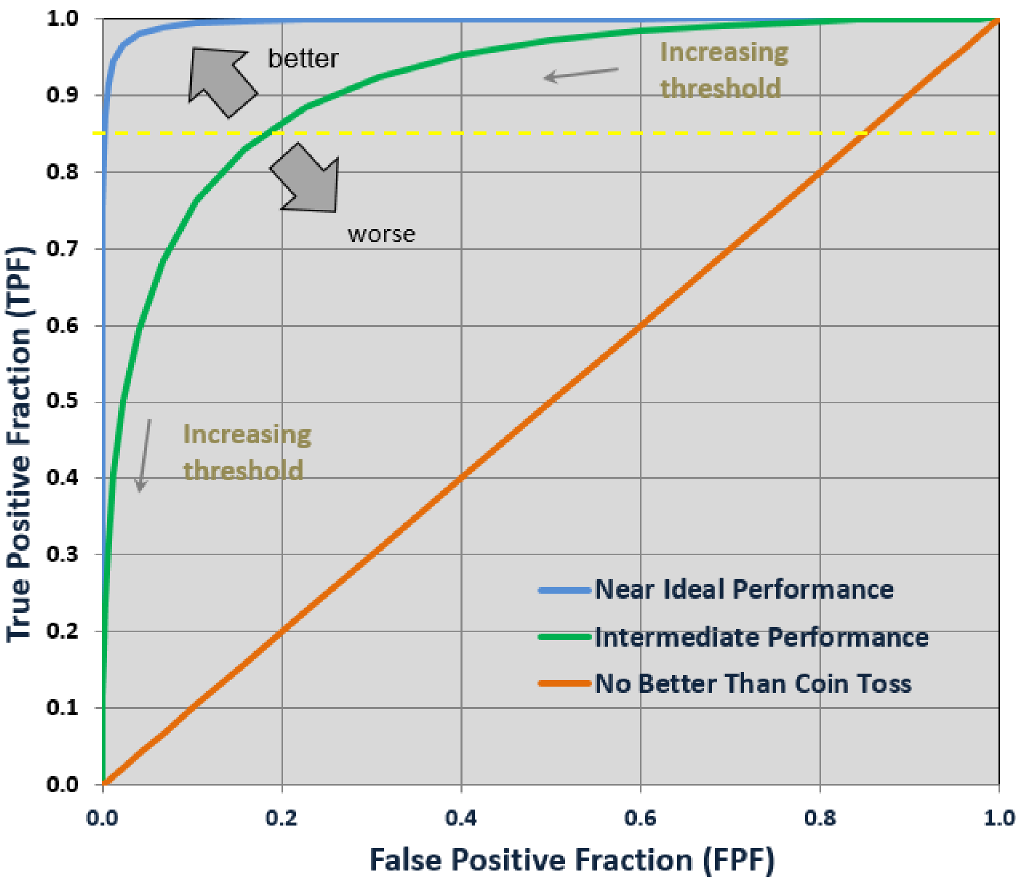

What is it?

- OC Curve: plot of TPF vs FPF

Definitions:

- False Positive: when a non-threat produces an alarm
- True Positive: when a true threat produces an alarm

Why is it useful?

- Permits fair performance comparison of two or more systems
- Consider two systems with the same TPF (yellow dashed line)
- At 85% TPF, the blue curve shows a false alarm rate of <0.3%. At the same TPF, the green curve shows a false alarm rate of 20%.
- The blue curve is always better than the green curve.

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